CAB-Fuzz: Practical Concolic Testing Techniques for COTS Operating Systems

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The Affiliated Institute of ETRI   Georgia Institute of Technology   Purdue University
Why Microsoft can’t detect a driver with a bug (NDProxy)?

```c
bool flag_table[125] = {false};
void (*fn_table[36])();

int dispatch_device_io_control(ulong ctrl_code, ulong *buf) {
    switch (ctrl_code) {
    case 0x8fff23c4:
        ...
    case 0x8fff23cc:
            return -1;
        if (flag_table[buf[1]])
            (*fn_table[buf[2]])();

        for (int i=1; i<=buf[0]; ++i) {...}
    }
    ...
}
```

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Why Microsoft can’t detect a driver with a bug (NDProxy)?

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bool flag_table[125] = {false};
void (*fn_table[36])();
```

Microsoft’s large-scale fuzzing tools couldn’t this bug

```c
case 0x8fff23cc:
    return -1;
  if (flag_table[buf[1]])
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for (int i=1; i<=buf[0]; ++i) {...}
```

Challenge 1: Path explosion because of array and loop

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            if (flag_table[buf[1]])
                (*fn_table[buf[2]])();
            for (int i=1; i<=buf[0]; ++i) {...}
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```

*Symbolic variables*
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        for (int i=1; i<=buf[0]; ++i) {...}
    }
}
```

Symbolic variables

Symbolic memories
Challenge 1: Path explosion because of array and loop

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int dispatch_device_io_control(ulong ctrl_code, ulong *buf) {
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        for (int i=1; i<=buf[0]; ++i) {...}
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```
Challenge 1: Path explosion because of array and loop

```c
bool flag_table[125] = {false};
void (*fn_table[36])();
```

More than million paths (124 x 36 x 246) to explore because of two arrays and a single loop

```c
case 0x8fff23cc:
        return -1;
    if (flag_table[buf[1]])
        (*fn_table[buf[2]])();
    for (int i = 1; i <= buf[0]; ++i) {...}
}  
```

Symbolic memories
Loop controlled by a symbolic variable
Challenge 1: Path explosion because of array and loop

• The number of feasible program paths to test exponentially increases according to its size
• COTS OS is complex and huge
• Almost infinite number of paths to test
Challenge 2: Difficulty in constructing pre-contexts to test targets

```c
bool flag_table[125] = {false}; // default: false
void (*fn_table[36])(());

int dispatch_device_io_control(ulong ctrl_code, ulong *buf)
{
    switch (ctrl_code) {
    case 0x8fff23c4:
        for (int i=0; i<125; ++i)
            flag_table[i] = true;
    case 0x8fff23cc:
        ...
        if (flag_table[buf[1]])
            (*fn_table[buf[2]])();
    }
```

Challenge 2: Difficulty in constructing pre-contexts to test targets

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bool flag_table[125] = {false}; // default: false
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int dispatch_device_io_control(ulong ctrl_code, ulong *buf)
{
    switch (ctrl_code) {
    case 0x8fff23c4:
        for (int i=0; i<125; ++i)
            flag_table[i] = true;
    case 0x8fff23cc:
        ...
        if (flag_table[buf[1]])
            (*fn_table[buf[2]])();
    }
```

should be executed to trigger the bug
Challenge 2: Difficulty in constructing pre-contexts to test targets

```c
bool flag_table[125] = {false}; // default: false
void (*fn_table[36])();
```

Difficult to construct pre-contexts to trigger bugs

```c
for (int i=0; i<125; ++i)
    flag_table[i] = true;
case 0x8fff23cc:
    ...
    if (flag_table[buf[1]])
        (*fn_table[buf[2]])();
} should be executed to trigger the bug
```
Challenge 2: Difficulty in constructing pre-contexts to test targets

• Many functions and code blocks have pre-contexts to execute them correctly
  • Execution order to set up states (open before read), input validation (checksum), ...

• Difficult to construct or guess pre-contexts
Challenge 2: Difficulty in constructing pre-contexts to test targets

• Many functions and code blocks have pre-contexts to execute them correctly
  • Execution order to set up states (open before read), input validation (checksum), ...

Research goal: Can we make a concolic testing tool that

1) avoids path explosion and
2) constructs pre-contexts automatically?
Idea 1: Test paths likely having bugs first

- Prioritize **array and loop boundary states**
- Detect bugs due to a lack of proper boundary checks
Idea 2: Construct pre-contexts using real programs

• Let real programs run until they call target OS APIs
  • Would have prepared necessary conditions before calling the APIs (they will call open syscall before read syscall)

• Hook the API calls and initiate concolic testing
Promising results

• Implemented by modifying S2E and evaluated with Windows 7 and Windows Server 2008

• Found 21 unique crashes in six device drivers
  • Two local privilege escalation vulnerabilities
  • Information disclosure in a crypto driver
Overview of CAB-Fuzz

COTS OSes (e.g., Windows)

disk image

1 Symbolization (synthetic or on-the-fly)

2 Concolic execution

BSOD detector

3 Analyzing crashes

Crash DB (e.g., memory dump)

Vuln. info (e.g., classification)
Synthetic symbolization with S2E

```c
ulong ctrl_code = 0; ulong in_buf[IN_BUF_SIZE] = {0};

NtCreateFile(&device_handle, ..., &object_attributes, ...);

s2e_make_symbolic(&ctrl_code, sizeof(ctrl_code), "code");

s2e_make_symbolic(&in_buf, sizeof(in_buf), "buf");

NtDeviceIoControlFile(
    device_handle, NULL, NULL, NULL,
    &io_status_block,
    ctrl_code, &in_buf, IN_BUF_SIZE,
    &out_buf, OUT_BUF_SIZE);
```
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Specify target API
Synthetic symbolization with S2E

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```

Specify target drivers
Symbolize two arguments
Specify target API
Don’t symbolize the size to avoid path explosion
Array-boundary prioritization

• Concretize the lowest and highest addresses of symbolic memory first

• Compute the boundary addresses using KLEE solver’s getRange function
  • For symbolic memory triggering a state fork at least twice
Loop-boundary prioritization

• Concretize a loop as no loop execution, a single execution, and the maximum executions

• Use a fork-and-kill approach to deal with unclear loop conditions and structures
  • Let a loop execute until it forks no more states (maximum)
  • Kill or pause uninteresting loop states
Prioritization reduces # of state forks to detect a bug

... if (buf[0]>246 &&
    buf[1]>124 &&
    buf[2]>36)
    return -1;
if (flag_table[buf[1])
    (*fn_table[buf[2]])();
for (int i=1; i<=buf[0];
    ++i) {...
...
Prioritization reduces # of state forks to detect a bug

```c
if (flag_table[buf[1])
  (*fn_table[0])();
for (int i=1; i<=buf[0];
    ++i) {...}
```

```c
if (flag_table[buf[1])
  (*fn_table[0])();
for (int i=1; i<=0;
    ++i) {...}
```

```c
if (flag_table[buf[1])
  (*fn_table[0])();
for (int i=1; i<=1;
    ++i) {...}
```

```c
if (flag_table[buf[1])
  (*fn_table[0])();
for (int i=1; i<=246;
    ++i) {...}
```
Prioritization reduces # of state forks to detect a bug

```
... if (buf[0]>246 && buf[1]>124 && buf[2]>36) return -1;
if (flag_table[buf[1]]) (*fn_table[buf[2]])();
for (int i=1; i<=buf[0]; ++i) {...}
...
```

__Crash!__
On-the-fly symbolization

Run a real program
On-the-fly symbolization

Run a real program

Interact with kernel

User-space

Kernel-space

Program

Kernel

Kernel data structures

Global variables
On-the-fly symbolization

Run a real program

Call a target function with valid arguments

Interact with kernel

Hooking

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Global variables
On-the-fly symbolization

Run a real program

Call a target function with valid arguments

Interact with kernel

Initiate concolic testing

User-space

Kernel-space

Program

Kernel

Kernel data structures

Global variables

Hooking
Evaluation

• How efficiently did CAB-Fuzz detect the known vulnerability (NDProxy)?
• How many new crashes did CAB-Fuzz discover?
• What particular characteristics did the newly discovered crashes exhibit?
CAB-Fuzz crashed NDProxy within two seconds

~2 hours!

Time (s) | 0 | 2000 | 4000 | 6000 | 8000
---|---|---|---|---|---
No prioritization | | | | | ~2 hours!
Prioritization | 2 s | | | | 

#Explored States | 0 | 100000 | 200000 | 300000 | 400000
---|---|---|---|---|---
No prioritization | | | | | 
Prioritization | | 78 | | |
CAB-Fuzz found 21 new crashes

• Synthetic symbolization
  • 274 device drivers in Windows 7 and Windows Server 2008

• On-the-fly symbolization
  • 16 real programs and 15 drivers the programs used

➢ Found 21 crashes in six among the drivers
CAB-Fuzz found 21 new crashes

Synthetic symbolization

- No prioritization
- Prioritization
- On-the-fly

<table>
<thead>
<tr>
<th>Software</th>
<th>NDIS</th>
<th>SrvAdmin</th>
<th>NSI</th>
<th>ASYNCMAC</th>
<th>FileInfo</th>
<th>ehdrv</th>
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CAB-Fuzz found 21 new crashes

A lack of memory (path explosion)
CAB-Fuzz found 21 new crashes

A lack of memory (path explosion)

No prioritization
Prioritization
On-the-fly

Pre-contexts needed

Synthetic symbolization

#Crashes

0 2 4 6 8 10

NDIS  SrvAdmin  NSI  ASYNCMAC  FileInfo  ehdrv
CAB-Fuzz found 21 new crashes

A lack of memory (path explosion)

Invalid pre-context needed

Pre-contexts needed

#Crashes

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<th>Library</th>
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<th>Invalid pre-context needed</th>
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CAB-Fuzz found 21 new crashes

A lack of memory (path explosion)
No program for on-the-fly
Invalid pre-context needed
Pre-contexts needed

Synthetic symbolization

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A lack of memory (path explosion)

No program for on-the-fly

Invalid pre-context needed

Pre-contexts needed

Synthetic and on-the-fly symbolizations are complementary to each other
What pre-contexts did drivers need?

• Selectively loaded (FileInfo)
  • Filesystem filter driver by Microsoft
  • Loaded only when a certain program started

• Access controlled (ehdrv)
  • Driver installed by antivirus software ESET Smart Security
  • Only accessible by the antivirus software itself
Prioritization reduced CPU time and memory usage
Limitations

• Reduce code coverage when prioritizing symbolic memory with instruction addresses (e.g., jump table)
• Cannot get boundary states from flexible data structures (e.g., linked list)
Limitations

• Have difficulties in regenerating on-the-fly-driven crashes
  • Lack of explicit control of pre-contexts construction

• Need to specify target APIs and programs
Conclusion

• CAB-Fuzz: A practical concolic testing tool for COTS OS
  • Check potentially vulnerable paths first
  • Analyze COTS OS without debug information and pre-contexts

• Found 21 crashes including three vulnerabilities with CVEs